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NRL Report 8066

# Heat Conduction in Three Dimensions

S. T. HANLEY

*High Energy Laser Facility  
Optical Sciences Division*

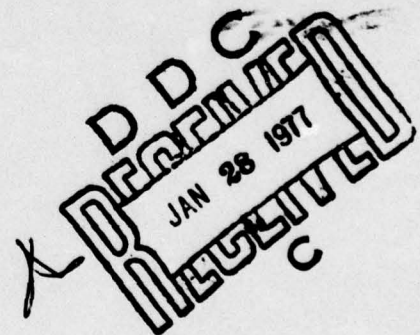
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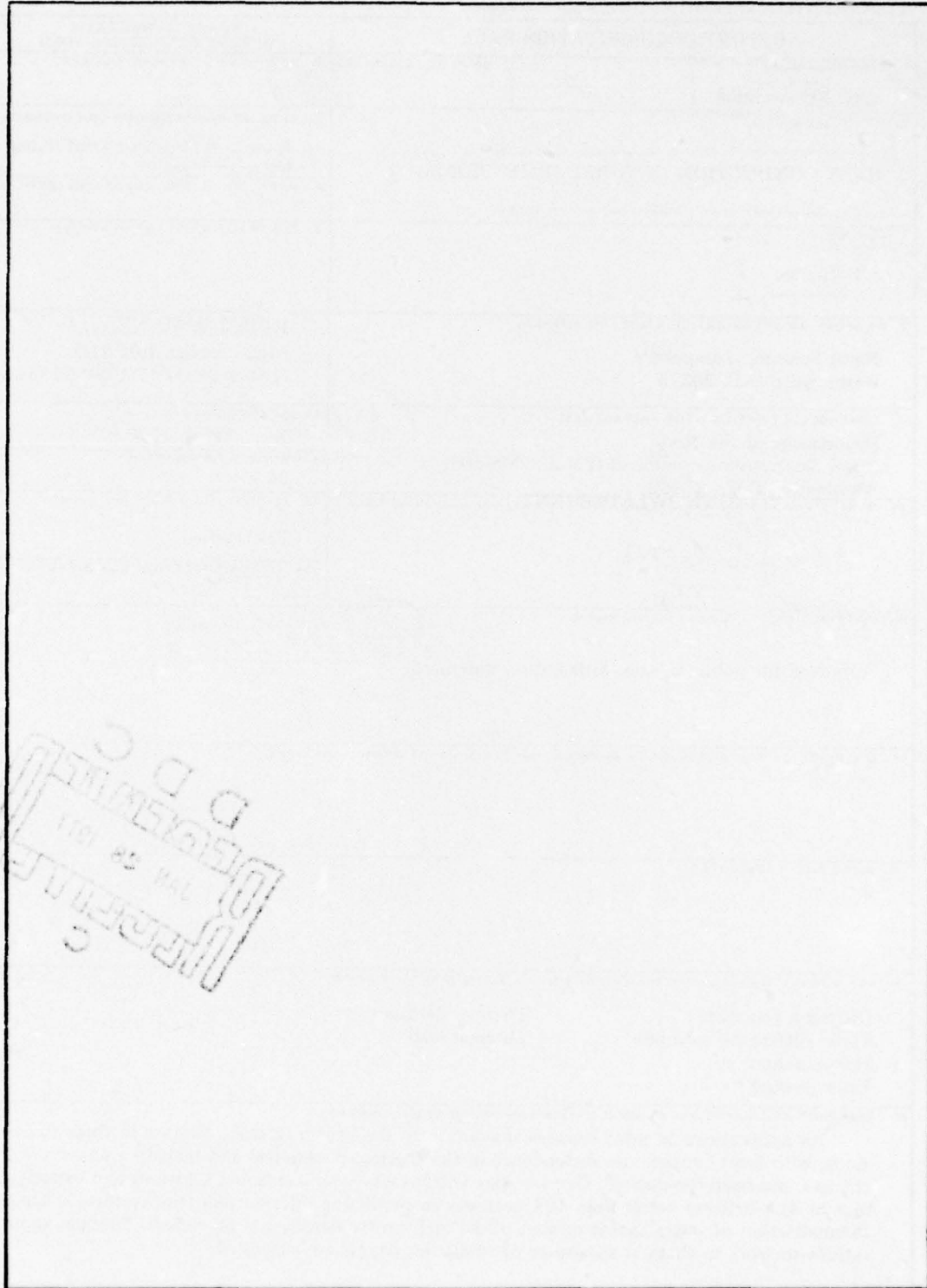
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## HEAT CONDUCTION IN THREE DIMENSIONS

### INTRODUCTION

There is a need for accurate three-dimensional heat transport prediction in many areas of applied research, including solidification of molten materials, ablation of missile skins under aerodynamic heating, vulnerability of targets under thermal loads, and characterization of high-power mirror surfaces under extreme thermal loads. In some cases the problem can adequately be described by unidimensional heat flux, but many problems cannot be solved in a convenient and general form without the added dimensions of transverse heat flow. The ongoing laser damage and vulnerability program in the Department of Defense could more effectively make use of limited test schedules with the aid of a three-dimensional code combining accuracy and computational ease. Despite the importance of the topic, the literature reveals few solutions that may be extended to practical problems of the type proposed here.

In an effort to satisfy this need, and in particular to characterize some high-power water-cooled mirrors for future use at the Optical Radiation Laboratory at Chesapeake Beach, Md., a standard finite-difference approximation has been initiated to solve the three-dimensional heat diffusion equation

$$\frac{\partial T}{\partial t}(x, y, z, t) = \alpha \nabla^2 T(x, y, z, t). \quad (1)$$

The complete difference form of this equation is used to provide maximum execution speed for a modest lattice point density. Although there are more elaborate digital techniques which would afford improved accuracy with the same lattice density, the additional program complexity does not justify the slight increase in accuracy near the fusion front (see for example Murray and Landis [1]).

Comparisons have been made in the limiting case of a "flood-loaded" sample with unidirectional heat flow to an exact premelting solution for temperature rise in a semi-infinite slab in one dimension and to internal temperature profiles derived from a highly refined fifty-subdivision one-dimensional finite-difference code by S.T. Hanley [2]. The agreement is better than 10% both in internal temperature profile and in burn-through prediction.

### FINITE-DIFFERENCE MODEL

The material to be heated or cooled is modeled to a rectangular slab with arbitrary length, width, and thickness and with the thermal load applied to the front surface. Before heat can diffuse into the interior of the slab, a thermal "step" must take place at the front surface; this is described by the basic heat conduction equation,

$$-K \nabla T = P_0 A \quad (2)$$

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in which  $P_0$  is the incident heat flux and  $A$  is the absorption coefficient or fraction of incident power density coupled into the material.  $K$  is the thermal conductivity for the material and is treated as a temperature-dependent parameter. The finite-difference approximation used for this equation is given in the forward difference form by

$$T(i, j, k, \ell + 1) = T(i, j, k, \ell) + \frac{P_0}{K} A \cos \theta \Delta Z \quad (3)$$

where a cosine function has been introduced to allow arbitrary incidence angles  $\theta$  from normal to the front surface. The X-Y plane is chosen to be the front surface, with the origin at one corner. The subscripts  $i$ ,  $j$ , and  $k$  refer to lattice points along the X, Y, and Z axes, and  $\ell$  refers to integral multiples of the step  $\Delta t$  along the time axis. At present no loss terms are explicitly included for heat carried away by convective cooling or radiation from the front surface. Under many applications these terms represent a negligible fraction of the heat input ( $< 30 \text{ W/cm}^2$  for front surface temperatures less than 2000K). Loss terms of this type are implicitly treated in temperature-dependent absorption coefficient  $A$ , which also accounts for changes in surface reflectivity.

The complete difference approximation for the diffusion of heat into the interior of the slab is given by

$$\begin{aligned} T(i, j, k, \ell + 1) = & T(i, j, k, \ell) + \frac{\alpha \Delta t}{\Delta X^2} [T(i+1, j, k, \ell) + T(i-1, j, k, \ell)] \\ & + \frac{\alpha \Delta t}{\Delta Y^2} [T(i, j+1, k, \ell) + T(i, j-1, k, \ell)] \\ & + \frac{\alpha \Delta t}{\Delta Z^2} [T(i, j, k+1, \ell) + T(i, j, k-1, \ell)] \\ & - 2\alpha \Delta t \left( \frac{1}{\Delta X^2} + \frac{1}{\Delta Y^2} + \frac{1}{\Delta Z^2} \right) T(i, j, k, \ell). \end{aligned} \quad (4)$$

The usual simplification of choosing  $\Delta t$  such that the  $T(i, j, k, \ell)$  term vanishes cannot be made because of the temperature dependence of the diffusivity

$$\alpha(T) = \frac{K(T)}{C(T)\rho(T)}, \quad (5)$$

where  $\rho$  and  $C$  are the density and specific heat, respectively. The code does select a time step  $\Delta t$  as a function of  $\Delta X$ ,  $\Delta Y$ ,  $\Delta Z$ , and the materials thermal parameters which will provide a stable convergent solution. Stability is taken in the sense that short-wave disturbances are damped out. A slight improvement in accuracy in the internal approximate solution to the diffusion equation was obtained by going to smaller time steps than that required for stability, with the lattice density remaining fixed in a manner analogous to the one-dimensional example given by Özisik [31].

The edge and back surfaces are independently constrained to satisfy one of two boundary conditions. The first is that of no heat flow across the boundary, resulting in

$$-K \nabla T = 0 \quad (6)$$

for all lattice points on that surface. A simple forward difference approximation to the gradient is used here, as in Eq. (3). The alternative boundary condition is to heat sink all lattice points in that surface to the ambient or initial slab temperature.

At the instant any lattice point reaches the melting temperature for the material, an additional boundary condition is applied:

$$\frac{\partial m}{\partial t} = \frac{K}{L} \sum_n \bar{\nabla}_n T_s - \frac{K}{L} \sum_n \bar{\nabla}_n T_\ell \quad (7)$$

where  $L$  is the latent heat of fusion for the material. This equation is used to follow the position of the liquid-solid interface along the permissible axis directions  $\pm i$ ,  $\pm j$ , and  $\pm k$ . Once a lattice point reaches the melt temperature it is pinned at the melt temperature until the heat flow into the unit cell about the lattice point minus the heat flow out, as evaluated with Eq. (7) along the six unit vector directions, is equal to the latent heat of melting for the mass of the unit cell. After this balance has been met, the lattice point temperature is allowed to rise. In this manner the melt surface progresses through the interior of the slab as dictated by the local thermal gradients. This model is quite powerful in dealing with irregular thermal load profiles on the front surface. Care must be taken to ensure that the time steps are small compared with the time required to melt a unit cell, in order to avoid excessive errors in fusion front travel. For the thermal loads considered here, this consideration is taken care of by the internal time step selection for stability.

A brief description of some of the program features will be given here, and a more detailed discussion of program construction and performance is given in Appendix A. The program has an internal library of materials containing thermal parameters with temperature dependence and is expandable to any material for which the constants are known. The lattice is made up of 10 equally spaced points per axis along the  $x$  and  $y$  axes and 11 equally spaced points along the  $z$  axis, providing an accuracy of better than 10% (as will be shown in the next section). The front surface thermal load is broken into three selectable categories. A "top hat" or uniform intensity distribution of arbitrary diameter and total power allows simulation of saturated laser amplifier configurations. A Gaussian distribution truncated at an arbitrary radius for the  $1/e^2$  intensity allows modeling of laser TEM<sub>00</sub> beam profiles. The third distribution allows the user to specify point by point an arbitrary thermal load application. This flexibility of input distribution allows modeling of a wide variety of problems with a minimum of setup time.

## APPLICATIONS

One of the first uses of the code was to scale high-reflectance water-cooled molybdenum mirrors with thermal load. An example of the predicted results is shown in Fig. 1. In the model, a truncated Gaussian beam of 4-cm radius impinges on a molybdenum slab of 0.05-cm

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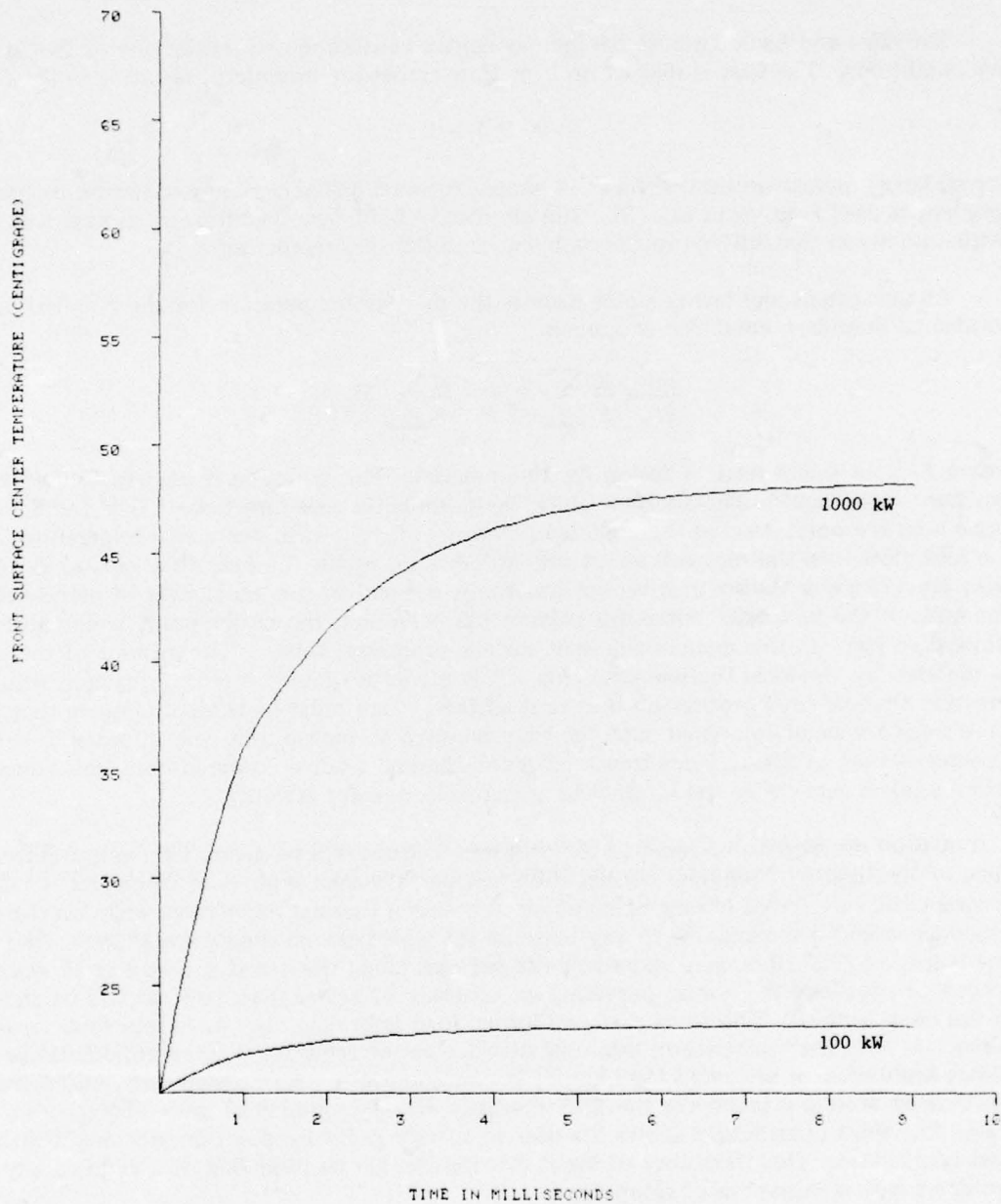


Fig. 1 — Thermal response of water-cooled molybdenum mirror. The front surface thermal response vs time is shown for a 98% reflective water-cooled molybdenum mirror at two power levels. The thermal load is produced by an 8-cm-diam Gaussian beam truncated at the  $1/e^2$  intensity radius and having 100-kW and 1000-kW total power to produce the upper and lower curves, respectively. Faceplate thickness is 0.05 cm.

thickness with the back surface and edges heat sunk to ambient temperature. The front surface reflectivity is set at a fixed 98% to allow for aging and accumulation of impurities. Although enhanced silver coatings are better than this [4], it is difficult to maintain higher reflectance than this over a period of time. Two power levels are shown; the lower one represents nominal power densities commonly in use on high-power water-cooled mirrors, and the upper curve represents an extrapolation to potentially attainable power densities. The cooling passages in the mirror wall allow some water temperature rise due to the finite flow rate through the mirror. At the higher power level, the water temperature rise from inlet to outlet may reach 10°C. This effect has not been included in the model, however, since it depends on the design of flow passages. The 0.05-cm face plate thickness represents that found in some of the better chemically etched mirrors on the market today. The time required to reach stable thermal conditions is short at both power levels. Figure 2 shows an overhead view of the molybdenum slab of Fig. 1, with the temperature axis normal to the front surface. The incident beam power differs slightly from 1000 kW due to the finite number of lattice sites within the beam diameter. Internal program algorithms were designed to preserve flux densities specified by total power and beam diameter and then print out the quantized beam power, rather than scale flux density to total power.

A check of premelting accuracy was made by flood loading a slab of aluminum with a uniform beam distribution for times shorter than that required for heat diffusion to the back surface and comparing the internal temperature profile to the exact one-dimensional analytical result

$$T(z, t) = T_0 + 2AP_0 \left[ \sqrt{\frac{t}{\pi K \rho C}} \exp\left(\frac{-Z^2 \rho C}{4Kt}\right) - \frac{z}{2K} \operatorname{erfc}\left(\frac{z}{2} \sqrt{\frac{\rho C}{Kt}}\right) \right] \quad (8)$$

for a semi-infinite slab of polished aluminum. The results after 0.05, 0.1, 0.15, and 0.2 s of irradiation are shown in Fig. 3. For purposes of comparison the temperature dependence of the thermal parameters in the three-dimensional code was suppressed. The upper curve of each pair is the three-dimensional finite-difference approximation to the exact one-dimensional analytical solution given in the lower curve. For all depths into the slab the accuracy is better than 10%. Several alternatives for improving accuracy are discussed in the subsequent section.

A limitation of thermal profiling models in the literature that claims high accuracy, such as the one-dimensional model of Fuhs and Fuhs [5], is the assumption of constant thermal parameters. To show the nature of this restriction, we irradiated a slab of polished aluminum with 20,000 W/cm<sup>2</sup> for 0.3 and 1.5 s. First with the temperature dependence contained in the thermal parameters and then with thermal dependence suppressed. The upper curve of each pair in Fig. 4 shows the error encountered by neglecting the temperature dependence. As might be expected, the error grows with increasing temperature and becomes appreciable after a modest amount of heating. In work on laser damage of materials such as the AVCO Everett study [6] done for the Air Force Materials Laboratory, significant improvement in modeling of experimental data should be obtained by including the effects of nonconstant specific heat, thermal conductivity, density, and absorption.

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MATERIAL: MOLYBD.

BEAM POWER: 1030619. WATTS

IRRADIATION TIME: 0.010 SEC.

ABSORPTION COEF. 0.02000

BEAM DIAMETER: 8.000 CM

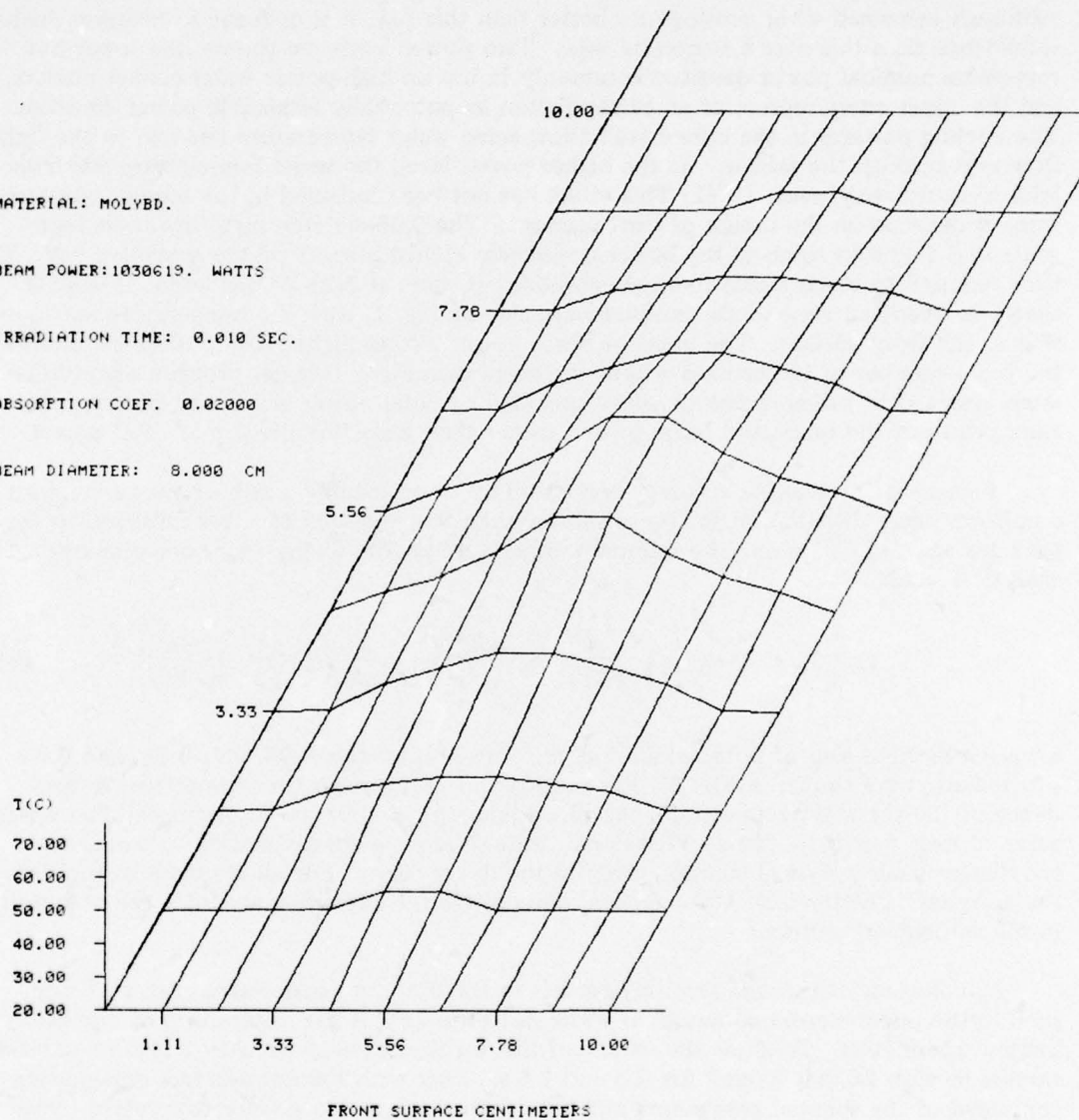


Fig. 2 — Surface plot of water-cooled molybdenum mirror under thermal load. Front surface temperatures. for a water-cooled molybdenum mirror under the conditions of Fig. 1 and at the 1000-kW power level. Shown after 10 ms of radiation.

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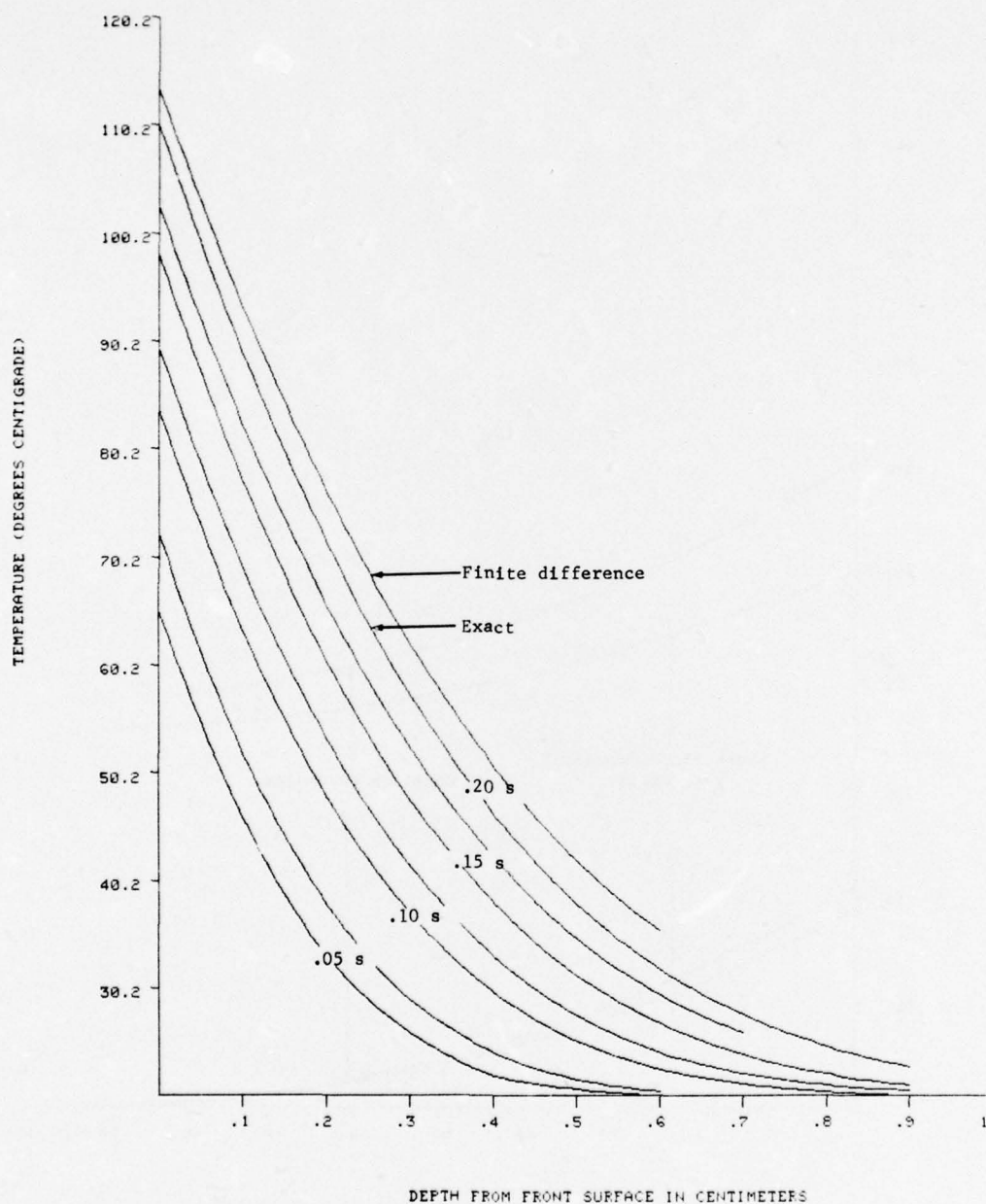


Fig. 3 — Comparison of three-dimensional code and one-dimensional analytical solution. The upper curve of each pair gives internal temperatures for a 1-cm-thick slab of aluminum 2024 uniformly flood loaded at 20000 W/cm<sup>2</sup> incident flux after 0.05, 0.1, 0.15, and 0.2 s of irradiation. Temperature dependence in all thermal parameters of the three-dimensional code are suppressed. The lower curve of each pair represents the exact one-dimensional analytical premelting solution for the same power density and at the respective times of irradiation.

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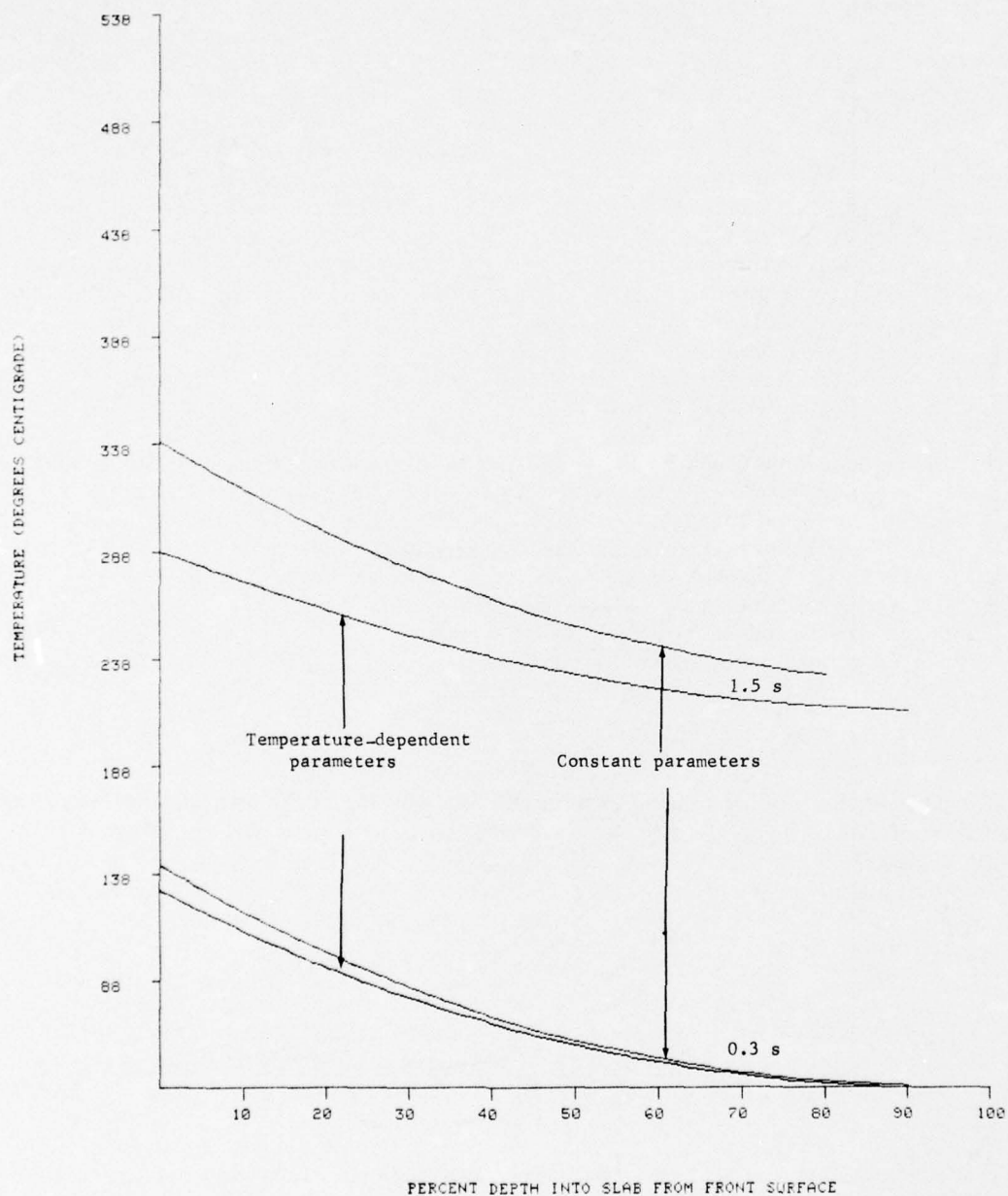


Fig. 4 — Temperature dependence in thermal parameters. Internal temperatures are shown for a 1-cm-thick slab of polished aluminum 2024 irradiated with  $20000 \text{ W/cm}^2$  in a flood-loaded uniform distribution for 0.3 and 1.5 s. The temperature dependence of thermal parameters was suppressed in the upper curve of each pair to show the error introduced by neglecting temperature dependence.

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Experimental measurements of burn-through times on aluminum panels painted with special "nonleafing" paint have been made by Dr. R. Wenzel of the Naval Research Laboratory (NRL). The samples were mounted vertically and irradiated at near normal incidence. Video coverage revealed retention of some liquid on the surface throughout the melting process. The measurements yielded a statistically averaged burn-through constant for given target thickness and irradiating peak power density. R.B. Brown, of NRL, performed absorption measurements on charred nonleafing paint samples and rough-melted aluminum samples at  $10.6\text{-}\mu\text{m}$  wavelengths. To test all of the features of the three-dimensional code, we ran a simulation of the painted aluminum sample. Using for inputs to the three-dimensional temperature profiler Brown's measured absorption values for premelting and postmelting, temperature-dependent thermal parameters for aluminum 2024, a slab thickness and power density equal to that used by Wenzel in his measurements, and 45% of total slab thickness retained as liquid, we heated the sample from  $20^\circ\text{C}$  up to melting, and the melt interface progressed to the back surface within 5% of the average burn-through time measured by Wenzel.

As an additional check on the validity of the three-dimensional code for heating beyond the onset of melting, a comparison was made to the exact one-dimensional burn-through expression in the limiting case of ablation (complete melt removal) and constant thermal parameters derived by J. Rogerson [7]. Burn through occurred in 5.78 s for a flood-loaded (beam diameter larger than sample) uniform beam of  $20,000\text{ kW/cm}^2$  incident on a polished aluminum 2024 slab 1 cm thick with 10% liquid layer retention (minimum layer of 3-D code at present) and with temperature dependence suppressed. This compared favorably with Rogerson's exact value of 5.90 s under the same conditions.

## DISCUSSION

One of the problems facing experimentalists working in the area of laser interactions with materials is the higher cost per shot and longer down time that are inherent in the trend toward large chemical lasers as compared with gas dynamic lasers. With the increased premium placed on experimental runs, the ability of this code to predict trends and aid selection of experiment parameters for maximum effectiveness of limited data becomes a valuable asset.

An area particularly well suited to modeling of the type discussed in this paper is in the development of hot spot tracking. With the addition of radiative and convective loss terms at the surface, modeling to thermal signatures from targets irradiated with arbitrary beam profiles could be performed using the existing three-dimensional code. By further modifying the code to exclude certain of the lattice points in the slab, geometries other than flat surfaces may be used for target simulation. The simulated thermal signature could be used to evaluate proposed hot spot tracking techniques and as an input toward improving working systems.

At present there are no solutions in the literature capable of predicting spatial distortions of optical surfaces under thermal loads, with the exception of simplified one-dimensional analyses such as that given by Fuhs and Fuhs [5]. The three-dimensional code presented here can in its present state give temperature-vs-time histories for arbitrary

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thermal loading and boundary conditions, as shown in Figs. 1 and 2. With additions to the code, spatial distortion in the slab could be calculated directly from the slab temperature matrix at any given time. Such information could be used in all high-power optics configurations.

The error shown in Fig. 3, due to 10 subdivisions per axis and a standard finite-difference approach, can be reduced in several ways. The most straightforward would be to increase the lattice point density and thereby derive a better approximation to the derivatives in Eq. (1). This alternative also gives more surface lattice points with which to approximate beam profiles. On the other hand it would require more computation time and more memory space from the computer. A second alternative, which was demonstrated in one-dimension for finite-difference techniques by S.T. Hanley [2], is to expand the solution in spatial and time coordinates for improved accuracy with the same lattice density. There will be an increase in computation time with this alternative due to the increase in mathematical complexity. In the one-dimensional case mentioned above it was shown that comparable accuracy was achieved by either doubling the lattice density or using the coordinate expansion. As shown in Fig. 3, the nature of the error is a small offset or starting error in the time variable; the error remains essentially constant as heating progresses. An alternative procedure to increase accuracy would be to determine the offset as a function of lattice spacing, time step, and material parameters and start the time variable at a suitable positive offset value. To demonstrate the improvement in accuracy obtained by this last method, we determined the fixed time offset for the example used in Fig. 3; by starting the time variable at this positive value are obtained the agreement shown in Fig. 5. The accuracy is better than 2% throughout the depth of the slab and for all times greater than several offset steps.

A particular experimental problem in the laser heating of materials is measurement of the liquid layer retained on the front surface of the irradiated sample as burn-through progresses. This is difficult to measure directly and has a significant effect on burn-through times. Figure 6 shows back surface temperature rise vs time for a slab of aluminum 1 cm thick irradiated with a 44-kW Gaussian beam of 3-cm diameter and with 10%, 20%, 40%, 60%, and 100% liquid layers retained at the front surface as the melt progresses. The faster temperature rise corresponds with the thinner liquid layer retained. A measurement could be made with conventional back surface thermocouple techniques, and the melt layer could then be derived by comparison to a chart such as Fig. 6 for the slab under study.

#### ACKNOWLEDGMENTS

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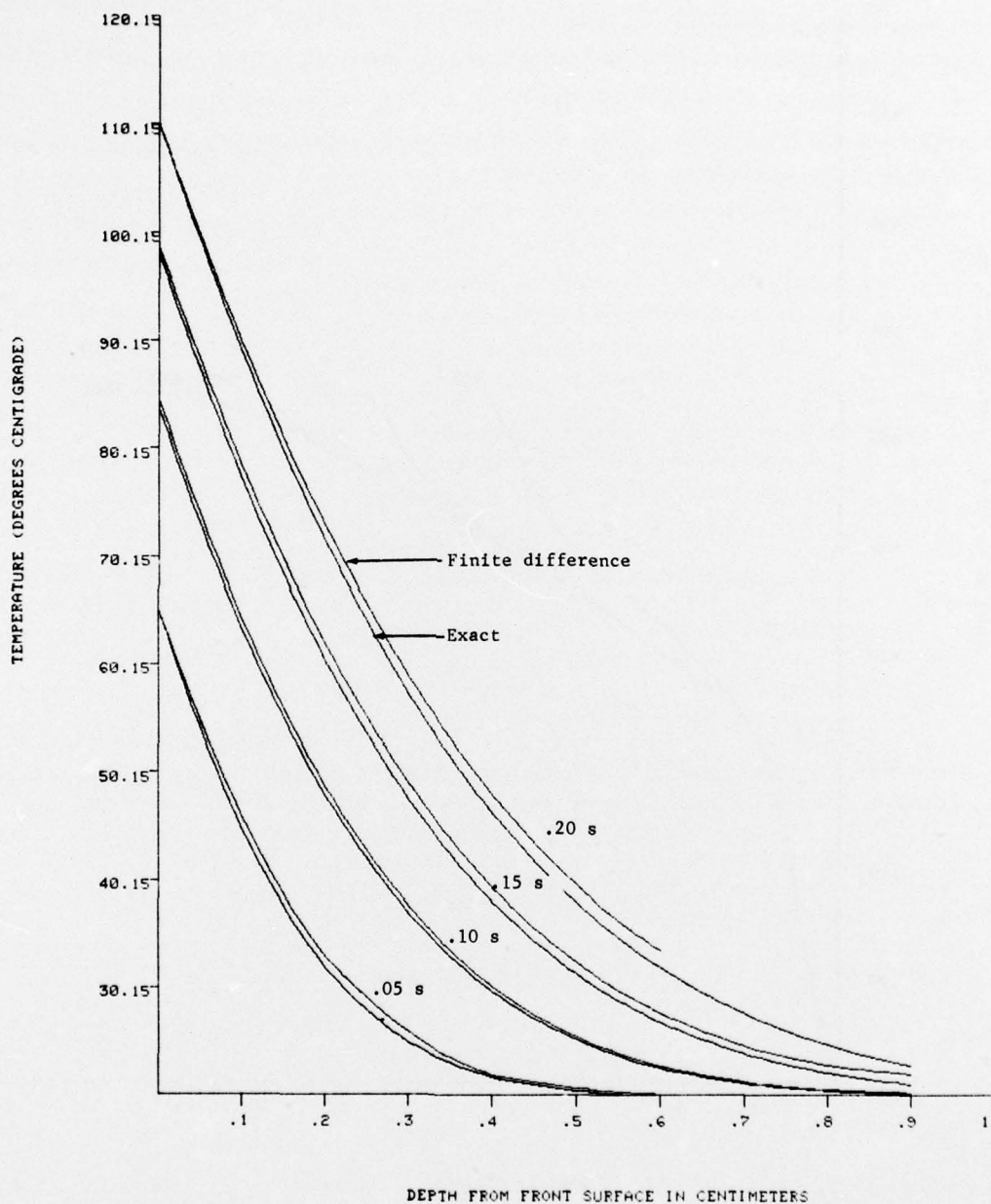


Fig. 5 — Improving accuracy by reducing starting error in time axis. Internal slab temperatures for aluminum 2024 under the conditions of Fig. 3 but with a time offset to reduce the starting error.

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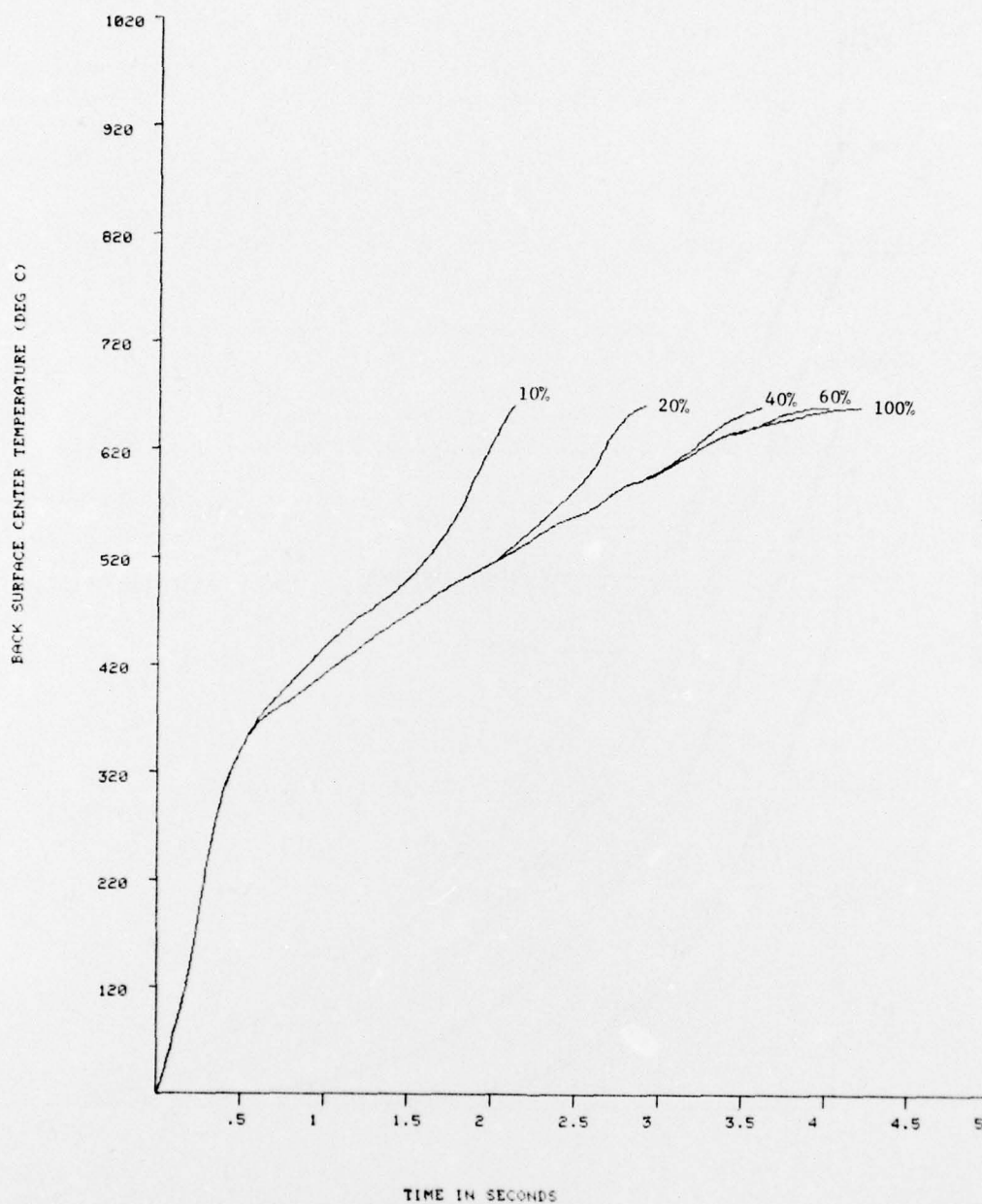


Fig. 6 — Back surface temperature signature vs melt removal. The center back surface temperature rise is given for a 1-cm-thick painted aluminum panel irradiated with a 3-cm truncated Gaussian beam of 44-kW total power at 10%, 20%, 40%, 60%, and 100% (of total slab thickness) liquid layer retention on front surface.

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## **Appendix A**

### **PROGRAM DESCRIPTION**

The program is set up so that with an initial terminal question-and-answer period the user can select a material, an arbitrary slab geometry, an arbitrary beam profile, and an arbitrary run time. An internal library contains all the material parameters and allows the user simply to select a material without the aid of reference tables. The target thickness, length, and width are input in centimeters. Beam characteristics are input as total power in watts, diameter in centimeters, angle of incidence in degrees from normal, and selection of Gaussian, "top-hat", or user-specified experimental profile. The ambient or starting temperature is input in degrees centigrade, and boundary conditions of heat sinking to ambient or insulating among edges and back surface are selected. Output graphics are set up by inputting total run time and printout time interval for slab temperature arrays and plot and either front or rear surface to be plotted.

The programing is done in Fortran IV for improved computation speed over Basic. The ratio of run times for the two programing languages on the PDP-11 is approximately 40 for a program of this type. The entire program is core resident on a 28K-PDP 11/40, including the plotting routine, and will cycle completely through one time step (once through program loop) in 1 s for premelting and 1.3 s for postmelting.

## Appendix B

### PROGRAM LISTING

```

0001      DIMENSION T0(10,10,11,2),IX0(8,8,9),P(10,10),IH2(10,10)
          1,IBUF(1200),O(10)
0002 10    FORMAT(' 1 ...ALUMINUM, 2 ...COPPER, 3 ...MOLYBDENUM,')
0003 20    FORMAT(' 4 ...IRON, 5 ...NICKEL, 6 ...TITANIUM, 7 ...AL(2024)')
0004 30    FORMAT(' INPUT # FOR TARGET MATERIAL')
0005 40    FORMAT(I4)
0006 50    FORMAT(' MATERIAL THICKNESS (CM)')
0007 60    FORMAT(F20.5)
0008 70    FORMAT(' TARGET LENGTH (CM)')
0009 80    FORMAT(' TARGET WIDTH (CM)')
0010 90    FORMAT(' AMBIENT TEMPERATURE (C)')
0011 100   FORMAT(' INCIDENT POWER (WATTS)')
0012 110   FORMAT(' BEAM DIAMETER (CM)')
0013 120   FORMAT(' ANGLE OF INCIDENCE (DEG) FROM NORMAL')
0014 125   FORMAT(' PREMELT ABSORPTION COEFFICIENT')
0015 126   FORMAT(' POST-MELTING ABSORPTION COEFFICIENT')
0016 130   FORMAT(' TIME OF RUN (SEC)')
0017 135   FORMAT(' PRINT OUT INTERVAL (SEC)')
0018 140   FORMAT(' PRINT X-AXIS INTERCEPT WITH Y-Z PLANE,1-9')
0019 145   FORMAT(' LIQUID LAYER RETAINED (PERCENT OF THICKNESS)')
0020 150   FORMAT(' SELECT MODE #')
0021 151   FORMAT(' 0 ...FRONT SURFACE PLOT')
0022 152   FORMAT(' 1 ...REAR SURFACE PLOT')
0023 155   FORMAT(' 1 ...EDGES INSULATED,BACK SURFACE INSULATED')
0024 160   FORMAT(' 2 ...EDGES HEAT SINKED TO AMBIENT,BACK SURFACE
          1 INSULATED')
0025 165   FORMAT(' 3 ...EDGES INSULATED,BACK SURFACE HEAT SINKED TO
          1 AMBIENT')
0026 170   FORMAT(' 4 ...EDGES AND BACK SURFACE HEAT SINKED TO AMBIENT')
0027 172   FORMAT(' INCIDENT BEAM PROFILE')
0028 174   FORMAT(' 1 ...GAUSSIAN')
0029 176   FORMAT(' 2 ...TOP HAT')
0030 178   FORMAT(' 3 ...EXPERIMENTAL PROFILE')
0031 180   FORMAT(' FRONT SURFACE')
0032 182   FORMAT(10I6)
0033 184   FORMAT(' ELEMENT',I4,' INPUT WATTS/CM/CM')
0034 186   FORMAT(' BURN THROUGH HAS OCCURRED AT POSITION',I4,I4)
0035 188   FORMAT(' AND AT TIME',F10.5,' SECONDS')
0036 190   FORMAT(' TIME IN SECONDS',F10.5)
0037 191   FORMAT(' FRONT SURFACE')
0038 192   FORMAT(10F8.2)
0039 193   FORMAT(' BACK SURFACE')
0040 194   FORMAT(' X-Z SLICE AT Y=',I2)
0041 195   FORMAT(' RUN COMPLETED')
0042 197   FORMAT(F8.0,F8.3,F8.5,F8.4)
0043      TYPE 10
0044      TYPE 20
0045      TYPE 30
0046      ACCEPT 40,I11
0047      GO TO (200,210,220,230,240,241,242),I11
0048 200   A0=660.
0049      F0=.222
0050      F2=.497
0051      A3=2.7
0052      A4=94.
0053      F1=7.71E-5
0054      F3=9.0E-4

```

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0055		F4=0.
0056		F5=30.
0057		F9=2.43
0058		GO TO 300
0059	210	A0=1083.
0060		F0=,915
0061		F2=,918
0062		A3=8.89
0063		A4=42.
0064		F1=2.4E-5
0065		F3=-1.19E-4
0066		F4=0.
0067		F5=18.
0068		F9=8.217
0069		GO TO 300
0070	220	A0=2610.
0071		F0=,06162
0072		F2=,346
0073		A3=10.2
0074		A4=131.
0075		F1=2.2E-5
0076		F3=-3.46E-5
0077		F4=0.
0078		F5=10.
0079		F9=8.1
0080		GO TO 300
0081	230	A0=1535.
0082		F0=,1060
0083		F2=,108
0084		A3=7.85
0085		A4=65.
0086		F1=9.6E-5
0087		F3=-1.08E-5
0088		F4=0.
0089		F5=18.
0090		F9=6.88
0091		GO TO 300
0092	240	A0=1453.
0093		F0=,1095
0094		F2=,1425
0095		A3=8.75
0096		A4=73.
0097		F1=5.49E-5
0098		F3=-4.56E-5
0099		F4=0.
0100		F5=0.
0101		F9=7.9
0102		GO TO 300
0103	241	A0=1690.
0104		F0=,139
0105		F2=,0372
0106		A3=4.54
0107		A4=103.9
0108		F1=0.
0109		F3=-4.E-6
0110		F4=0.
0111		F5=21.

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0112      F9=4.09
0113      GO TO 300
0114 242   A0=630.
0115      F0=.215
0116      F2=.334
0117      A3=2.77
0118      A4=95.6
0119      F1=7.71E-5
0120      F3=9.0E-4
0121      F4=0.
0122      F5=30.
0123      F9=2.43
0124 300   TYPE 50
0125      ACCEPT 60,A6
0126      TYPE 70
0127      ACCEPT 60,A7
0128      TYPE 80
0129      ACCEPT 60,A8
0130      TYPE 90
0131      ACCEPT 60,A9
0132      TYPE 100
0133      ACCEPT 60,B0
0134      B0=B0/4.54
0135      TYPE 110
0136      ACCEPT 60,B1
0137      TYPE 120
0138      ACCEPT 60,B2
0139      TYPE 125
0140      ACCEPT 60,A5
0141      TYPE 126
0142      ACCEPT 60,AMS
0143      TYPE 130
0144      ACCEPT 60,B3
0145      TYPE 135
0146      ACCEPT 60,00
0147      TYPE 140
0148      ACCEPT 40,ID2
0149      C9=0.
0150      TYPE 145
0151      ACCEPT 40,IH1
0152      IH1=IH1/10,+.5
0153      TYPE 150
0154      TYPE 151
0155      TYPE 152
0156      ACCEPT 40,IPL
0157      IPL=1+10*IPL
0158      TYPE 155
0159      TYPE 160
0160      TYPE 165
0161      TYPE 170
0162      ACCEPT 40,IB5
0163      TYPE 172
0164      TYPE 174
0165      TYPE 176
0166      TYPE 178
0167      ACCEPT 40,IB6
0168      B7=AB/9.

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0169      B9=B1/B7
0170      B8=A7/9.
0171      C0=B1/B8
0172      GO TO (330,320,310),I86
0173 310   TYPE 180
0174      DO 312 I=1,10
0175      DO 311 J=1,10
0176      IBUF(J)=J-1+10*(I-1)
0177 311   CONTINUE
0178      TYPE 182,(IBUF(L),L=1,10)
0179 312   CONTINUE
0180      DO 314 I=1,10
0181      DO 314 J=1,10
0182      R0=(I-5.5)**2/B9/B9+(J-5.5)**2/C0/C0
0183      IF (R0.GT..25) GO TO 313
0185      K=I-1+10*(J-1)
0186      TYPE 184,K
0187      ACCEPT 60,F6
0188      P(I,J)=F6/4.54
0189      GO TO 314
0190 313   P(I,J)=0.
0191 314   CONTINUE
0192      GO TO 340
0193 320   C4=4.*B0/3.14159/B1/B1
0194      DO 322 I=1,10
0195      DO 322 J=1,10
0196      R0=(I-5.5)**2/B9/B9+(J-5.5)**2/C0/C0
0197      IF (R0.GT..25) GO TO 321
0199      P(I,J)=C4
0200      GO TO 322
0201 321   P(I,J)=0.
0202 322   CONTINUE
0203      GO TO 340
0204 330   DO 332 I=1,10
0205      DO 332 J=1,10
0206      R0=2.*(((I-5.5)*B7)**2+((J-5.5)*B8)**2)**.5
0207      IF(R0.GT.B1) GO TO 331
0209      E0=-2.*R0/B1
0210      P(I,J)=4.287*R0*EXP(E0)/B1/B1
0211      GO TO 332
0212 331   P(I,J)=0.
0213 332   CONTINUE
0214 340   D1=D0
0215      C1=0.
0216      DO 344 I=1,10
0217      DO 344 J=1,10
0218      DO 344 K=1,11
0219      T0(I,J,K,1)=A9
0220      T0(I,J,K,2)=A9
0221      IF(K.GT.9)GO TO 344
0223      IF(I.GT.8.OR.J.GT.8)GO TO 344
0225      IX0(I,J,K)=0
0226 344   CONTINUE
0227      C2=.2*(F0+F1*A9)*A3/(F2+F3*(A9-F5))/(1./B8/B8+1./E7/B7
1 +100./A6/A6)
0228      D6=C2/B7/B7
0229      C0=C2*100./A6/A6

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0230      C3=C2/B8/B8
0231      C4=2.*C2*(1./B8/B8+1./B7/B7+100./A6/A6)
0232      THET=3.14159*B2/180.
0233      G3=COS(THET)*A5*A6/5.
0234      B4=C2*10000./A4/A3/B8/B8
0235      B5=C2*10000./A4/A3/B7/B7
0236      B6=C2*1000000./A4/A3/A6/A6
0237      B0=0.
0238      DO 400 J=1,10
0239      DO 400 I=1,10
0240      IH2(I,J)=1
0241      B0=P(I,J)*B7*B8*4.54+B0
0242 400   CONTINUE
0243 500   IC1=8*C1+2
0244      DO 505 K=2,IC1
0245      DO 505 J=2,9
0246      DO 505 I=2,9
0247      IF(T0(I,J,K,1).LE.A0) GO TO 505
0249      IF(IX0(I-1,J-1,K-1).NE.0) GO TO 505
0251      T0(I,J,K,1)=A0
0252      IX0(I-1,J-1,K-1)=1
0253      IF(C1.GT..5)GO TO 505
0255      C1=1.
0256      G3=G3*AMS/A5
0257      A5=AMS
0258 505   CONTINUE
0259      DO 510 J=1,10
0260      DO 510 I=1,10
0261      I3=IH2(I,J)+1
0262      T0(I,J,I3-1,1)=(G3*P(I,J)/(F2+F3*(T0(I,J,I3,1)-F5))+
1 4*T0(I,J,I3,1)-T0(I,J,I3+1,1))/3.
0263 510   CONTINUE
0264      DO 525 K=2,10
0265      DO 525 J=2,9
0266      DO 525 I=2,9
0267      IF(T0(I,J,K,1).LE.A0) GO TO 522
0269      F8=F9
0270      GO TO 524
0271 522   F8=A3
0272 524   A1=(F2+F3*(T0(I,J,K,1)-F5))/F8/(F0+F1*T0(I,J,K,1))
0273      E0=A1*06*(T0(I,J+1,K,1)+T0(I,J-1,K,1))
0274      E1=A1*00*(T0(I,J,K+1,1)+T0(I,J,K-1,1))
0275      E2=A1*03*(T0(I+1,J,K,1)+T0(I-1,J,K,1))
0276      T0(I,J,K,2)=E0+E1+E2+(1.-A1*04)*T0(I,J,K,1)
0277 525   CONTINUE
0278      GO TO (530,535,540,550),IB5
0279 530   DO 532 J=1,10
0280      DO 532 I=1,10
0281      T0(I,J,11,2)=T0(I,J,10,2)
0282 532   CONTINUE
0283 540   DO 533 K=2,11
0284      DO 533 J=1,10
0285      T0(I,J,K,2)=T0(2,J,K,2)
0286      T0(10,J,K,2)=T0(9,J,K,2)
0287 533   CONTINUE
0288      DO 534 K=2,11
0289      DO 534 I=1,10

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0290      T0(I,1,K,2)=T0(I,2,K,2)
0291      T0(I,10,K,2)=T0(I,9,K,2)
0292 534    CONTINUE
0293      GO TO 550
0294 535    DO 537 J=1,10
0295      DO 537 I=1,10
0296      T0(I,J,11,2)=T0(I,J,10,2)
0297 537    CONTINUE
0298 550    IF(C1,LT,.5) GO TO 600
0300      DO 580 K=2,10
0301      DO 580 J=2,9
0302      DO 580 I=2,9
0303      IF(IX0(I-1,J-1,K-1),LE,0) GO TO 580
0305      C7=F2+F3*(T0(I,J,K,1)-F5)
0306      E0=T0(I-1,J,K,1)+T0(I+1,J,K,1)-2*T0(I,J,K,1)
0307      IX0(I-1,J-1,K-1)=IX0(I-1,J-1,K-1)+C7*E0*B4+.5
0308      IF(IX0(I-1,J-1,K-1),GT,0) GO TO 552
0310      IX0(I-1,J-1,K-1)=1
0311 552    IF(IX0(I-1,J-1,K-1),LE,10000) GO TO 554
0313      IX0(I-1,J-1,K-1)=-1
0314      IF(K-IH2(I,J),LT,IH1)GO TO 580
0316      IH2(I,J)=IH2(I,J)+1
0317      GO TO 580
0318 554    T0(I,J,K,2)=A0
0319 560    E0=T0(I,J-1,K,1)+T0(I,J+1,K,1)-2*T0(I,J,K,1)
0320      IX0(I-1,J-1,K-1)=IX0(I-1,J-1,K-1)+C7*E0*B5+.5
0321      IF(IX0(I-1,J-1,K-1),GT,0) GO TO 562
0323      IX0(I-1,J-1,K-1)=1
0324 562    IF(IX0(I-1,J-1,K-1),LE,10000) GO TO 564
0326      IX0(I-1,J-1,K-1)=-1
0327      IF(K-IH2(I,J),LT,IH1)GO TO 580
0329      IH2(I,J)=IH2(I,J)+1
0330      GO TO 580
0331 564    T0(I,J,K,2)=A0
0332 570    E0=T0(I,J,K-1,1)+T0(I,J,K+1,1)-2*T0(I,J,K,1)
0333      IX0(I-1,J-1,K-1)=IX0(I-1,J-1,K-1)+C7*E0*B6+.5
0334      IF(IX0(I-1,J-1,K-1),GT,0) GO TO 572
0336      IX0(I-1,J-1,K-1)=1
0337 572    IF(IX0(I-1,J-1,K-1),LE,10000) GO TO 574
0339      IF(K,EQ,10)GO TO 573
0341      IX0(I-1,J-1,K-1)=-1
0342      IF(K-IH2(I,J),LT,IH1)GO TO 580
0344      IH2(I,J)=IH2(I,J)+1
0345      GO TO 580
0346 573    TYPE 186,I,J
0347      TYPE 188,C9
0348      STOP
0349 574    T0(I,J,K,2)=A0
0350 580    CONTINUE
0351 600    C9=C9+C2
0352      IF(C9,LT,D1) GO TO 700
0354      D1=D1+D0
0355      TYPE 190,C9-C2
0356 610    TYPE 191
0357      DO 620 I=1,10
0358      DO 615 J=1,10
0359      IF(1,LT,IH2(I,J))GO TO 612

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0361      O(J)=T0(I,J,1,1)
0362      GO TO 615
0363 612    O(J)=1.E+9
0364 615    CONTINUE
0365      TYPE 192,(O(L),L=1,10)
0366 620    CONTINUE
0367      TYPE 193
0368      DO 630 I=1,10
0369      TYPE 192,(T0(I,L,11,1),L=1,10)
0370 630    CONTINUE
0371      TYPE 194,ID2
0372      DO 635 I=1,10
0373      DO 631 K=2,11
0374      IF(K.LT.IH2(I,ID2))GO TO 632
0376      O(K-1)=T0(I,ID2,K,1)
0377      GO TO 631
0378 632    O(K-1)=1.E+9
0379 631    CONTINUE
0380      TYPE 192,(O(L),L=1,10)
0381 635    CONTINUE
0382      E0=-500.
0383      E2=50000.
0384      DO 640 J=1,10
0385      DO 640 I=1,10
0386      IF(T0(I,J,IPL,1).LT.E0)GO TO 636
0388      E0=T0(I,J,IPL,1)
0389 636    IF(T0(I,J,IPL,1).GT.E2)GO TO 640
0391      E2=T0(I,J,IPL,1)
0392 640    CONTINUE
0393      IF(E0-E2.GT..1)GO TO 800
0395      E1=.1
0396      GO TO 850
0397 800    IF(E0-E2.GT.1.)GO TO 801
0399      E1=1.
0400      GO TO 850
0401 801    IF(E0-E2.GT.5.)GO TO 802
0403      E1=5.
0404      GO TO 850
0405 802    IF(E0-E2.GT.10.)GO TO 803
0407      E1=10.
0408      GO TO 850
0409 803    IF(E0-E2.GT.50.)GO TO 804
0411      E1=50.
0412      GO TO 850
0413 804    IF(E0-E2.GT.100.)GO TO 805
0415      E1=100.
0416      GO TO 850
0417 805    IF(E0-E2.GT.500.)GO TO 806
0419      E1=500.
0420      GO TO 850
0421 806    IF(E0-E2.GT.1000.)GO TO 807
0423      E1=1000.
0424      GO TO 850
0425 807    E1=3000.
0426 850    SCA=125./E1
0427      CALL INIT(IBUF,1120)
0428      CALL SCAL(0.,0.,970.,1000.)

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0429      CALL APNT(100.,100.,-1,-1,0)
0430      CALL VECT(500.,750.,-1,-6,-1,1)
0431      CALL APNT(100.,240.,-1,-1,0)
0432      CALL VECT(0.,-140.,-1,-6,-1,0)
0433      CALL VECT(500.,0.,-1,-6,-1,1)
0434      DO 645 I=1,5
0435      CALL APNT(I*100.,+50.,+90.,-1,-6,0)
0436      CALL VECT(0.,10.,-1,-6,-1,1)
0437 645   CONTINUE
0438      DO 647 I=1,5
0439      CALL APNT(I*100.,+40.,I*150.,+25.,-1,-6,0)
0440      CALL VECT(10.,0.,-1,-6,-1,1)
0441 647   CONTINUE
0442      DO 650 I=1,6
0443      CALL APNT(90.,100.,+(I-1)*25.,-1,-6,0)
0444      CALL VECT(10.,0.,-1,-6,-1,1)
0445 650   CONTINUE
0446      DO 660 J=1,10
0447      CALL APNT(50.,+J*50.,(T0(I,J,IPL,1)-E2)*SCA+25.,+J*75.,-1,-5,-1)
0448      DO 660 L=1,9
0449      CALL VECT(50.,(T0(L+1,J,IPL,1)-T0(L,J,IPL,1))*SCA,-1,5,-1,1)
0450 660   CONTINUE
0451      DO 662 I=1,10
0452      CALL APNT(50.,+I*50.,(T0(I,1,IPL,1)-E2)*SCA+100.,-1,5,-1,1)
0453      DO 662 L=1,9
0454      CALL VECT(50.,(T0(I,L+1,IPL,1)-T0(I,L,IPL,1))*SCA+75.,-1,5,-1,1)
0455 662   CONTINUE
0456      CALL APNT(20.,250.,-1,-6,0)
0457      CALL TEXT(' T(C) ')
0458      CALL APNT(300.,20.,-1,-6,0)
0459      IF(IPL,LT,5)GO TO 665
0461      CALL TEXT(' REAR SURFACE CENTIMETERS')
0462      GO TO 670
0463 665   CALL TEXT(' FRONT SURFACE CENTIMETERS')
0464 670   CALL APNT(0.,725.,-1,-6,0)
0465      CALL TEXT(' 3-D TEMPERATURE PROFILE')
0466      DO 675 I=1,5
0467      CALL APNT(I*100.,-15.,70.,-1,-6,0)
0468      CALL NMRR(I,2*88*(I-.5),F7,2)
0469 675   CONTINUE
0470      DO 680 I=2,5
0471      CALL APNT((I-.5)*100.,I*150.,+15.,-1,-6,0)
0472      CALL NMRR(I+.5,2*87*(I-.5),F7,2)
0473 680   CONTINUE
0474      DO 685 I=1,6
0475      CALL APNT(0.,90.,+(I-1)*25.,-1,-6,0)
0476      IF(E1,GT,50.)GO TO 684
0478      CALL NMRR(I+11,(I-1)*25./SCA+E2,F6,2)
0479      GO TO 685
0480 684   CALL NMRR(I+11,(I-1)*25./SCA+E2,F6,0)
0481 685   CONTINUE
0482      CALL APNT(0.,700.,-1,-6,0)
0483      CALL TEXT('PREPARED BY DR S.T.HANLEY N R L')
0484      CALL APNT(0.,675.,-1,-6,0)
0485      CALL TEXT('MATERIAL:')
0486      CALL APNT(141.,675.,-1,-6,0)
0487      GO TO (690,691,692,693,694,810,811),I11

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0488 690 CALL TEXT('ALUMINUM')
0489      GO TO 695
0490 691 CALL TEXT('COPPER')
0491      GO TO 695
0492 692 CALL TEXT('MOLYBD.')
0493      GO TO 695
0494 693 CALL TEXT('IRON')
0495      GO TO 695
0496 694 CALL TEXT('NICKEL')
0497      GO TO 695
0498 810 CALL TEXT('TITANIUM')
0499      GO TO 695
0500 811 CALL TEXT('AL(2024)')
0501 695 CALL APNT(0.,650.,-1,-6.0)
0502      CALL TEXT('BEAM POWER:')
0503      CALL APNT(156.,650.,-1,-6.0)
0504      CALL NMBR(21,B0,'F8.0')
0505      CALL APNT(290.,650.,-1,-6.0)
0506      CALL TEXT('WATTS')
0507      CALL APNT(0.,625.,-1,-6.0)
0508      CALL TEXT('IRRADIATION TIME:')
0509      CALL APNT(223.,625.,-1,-6.0)
0510      CALL NMBR(22,C9-C2,'F8.3')
0511      CALL APNT(350.,625.,-1,-6.0)
0512      CALL TEXT('S ')
0513      CALL APNT(0.,600.,-1,-6.0)
0514      CALL TEXT('ABSORPTION COEF. ')
0515      CALL APNT(238.,600.,-1,-6.0)
0516      CALL NMBR(23,A5,'F8.5')
0517      CALL APNT(0.,575.,-1,-6.0)
0518      CALL TEXT('BEAM DIAMETER:')
0519      CALL APNT(193.,575.,-1,-6.0)
0520      CALL NMBR(24,B1,'F8.3')
0521      CALL APNT(335.,575.,-1,-6.0)
0522      CALL TEXT('CM')
0523 700 IF(C9.GT.B3.OR.C9.EQ.B3) GO TO 750
0525      DO 710 K=1,11
0526      DO 710 J=1,10
0527      DO 710 I=1,10
0528          T0(I,J,K,1)=T0(I,J,K,2)
0529 710 CONTINUE
0530      GO TO 500
0531 750 TYPE 195
0532      END

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